
F. Johannaber

INJECTION

MOLDING

MACHINES

A User's Guide



Distributed in the United States of America
by Macmillan Publishing Co., Inc., New York

Distributed in Canada
by Collier Macmillan Canada, Ltd., Toronto

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Translation of an extension of the chapter "Spritzgießmaschinen" from the book *Kunststoffmaschinenführer*, Stoeckhert/Schaab, Carl Hanser Verlag, Munich, West Germany, 1979.

Distributed in USA by
Scientific and Technical Books
Macmillan Publishing Co., Inc.
866 Third Avenue, New York, N. Y. 10022

Distributed in Canada by
Collier Macmillan Canada Distribution Center
539 Collier Macmillan Drive, Cambridge, Ontario

Distributed in all other countries by
Carl Hanser Verlag
Kolbergerstraße 22
D-8000 München 80

CIP-Kurztitelaufnahme der Deutschen Bibliothek

Johannaber, Friedrich:

Injection molding machines : a user's guide /

F. Johannaber. [Transl. by Rolf J. Kahl]. –

München ; Wien : Hanser, 1983.

Einheitssacht.: Spritzgiessmaschinen (engl.)

ISBN 3-446-13757-8

ISBN 3-446-13757-8 Carl Hanser Verlag München Wien
ISBN 0-02-949420-6 Macmillan Publishing Co., Inc., New York

Library of Congress Catalog Card Number 81-85871

Cover design: C.-A. Loipersberger

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Printed in Germany by Sellier Druck GmbH, Freising

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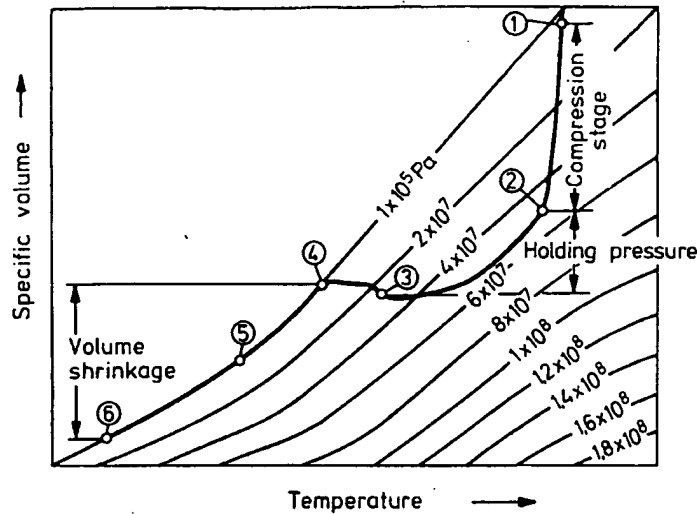


Figure 21 $p-v-T$ diagram (schematic) of thermoplastics and cavity pressure drop [9].

2.4.2 Mechanical and Physical Properties

The mechanical and physical properties of molded parts, particularly those made of thermoplastics, do not depend only on the chemical constitution of the material and its corresponding properties. The processing conditions exercise a considerable influence, either as an inevitable or selected effect. Properties of use such as strength, toughness, hardness, heat distortion, dimensional stability, and tendency to stress cracking may vary, more or less, with one and the same material, or can be selectively varied depending on the processing technique. Those factors that determine the part quality frequently are not apparent externally, but are reflected by the internal structure of the part.

The most important structural characteristics of thermoplastics dependent on processing conditions are:

- Molecular orientation

- Residual stresses

- Crystalline structure and degree of crystallinity (of partly crystalline materials)

- Orientation of fillers (of filled or glass-reinforced materials)

Possible changes in the molecular structure through reduction of the chain length or degradation are not discussed here. The factors responsible for this result from residence time in the barrel, melt temperature, and an intense shear effect in the runner system during injection.

2.4.2.1 Molecular Orientation

Molecular orientation is the alignment of molecular chains in one particular direction. In a plastic melt at rest, individual molecular segments are, or rather move about, in a random, tangled state of maximum irregularity. As they flow during the forming process, for example, during injection, the molecular chains are forced into a preferred direction; they take on a particular orientation. Orientation, as schematically shown in Fig. 22, occurs during flow in channels, either in injection molds or in extruder dies.

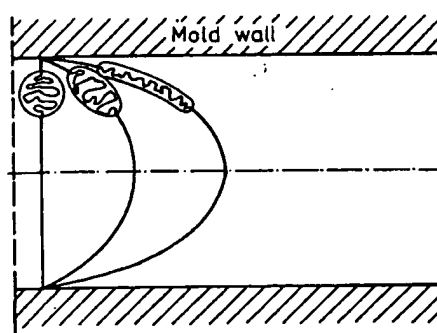


Figure 22 Formation of molecular orientation [10]. An originally circular segment is deformed by the flow of melt, which causes the molecular chains to become oriented in the direction of flow.

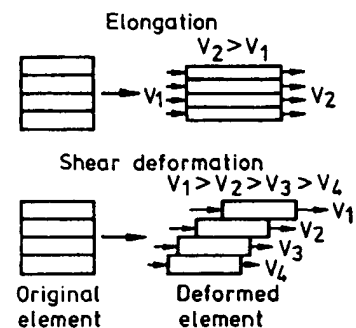


Figure 23 Elongation and shear deformation of segments of melt caused by velocity differential [10].

The shear velocity in molten plastics is especially high in narrow channels and in areas close to the cavity wall, where the melt is also stretched (Fig. 23). The melt tends to adhere to the cavity wall, while it flows rapidly in the center of the part. When the oriented melt comes to a standstill, the molecular chains, after some time, regain their irregular, random state due to their thermal motion (Brownian motion). This process is called relaxation. The relaxation rate depends on the structure of the molecules and the properties of eventually used additives (internal lubricants), as well as upon temperature and pressure. Low molecular weight, high temperature, and low pressure promote higher relaxation rates.

In any case the plastic melt relaxes within a few seconds at the temperatures customary in injection molding. On the other hand, it usually takes only a fraction of a second, especially in the surface layers, for the material to solidify, and a considerable part of the orientation

produced during molding is always "frozen in." With decreasing temperature, the relaxation velocity slows down very rapidly. Below the glass transition temperature, practically no relaxation takes place, provided the parts are not exposed to higher temperatures again later on.

Because the relaxation process of oriented plastic parts is always accompanied by shrinkage, the extent of shrinkage serves as a measure of the degree of orientation. Usually, orientation from injection molding is a very complex superimposition of shear deformation and elongation. Around a pinpoint gate, the melt experiences shearing action radially and elongation tangentially to the flow front (Fig. 24). The radial direction generally is called the direction of flow. This is not identical with the actual path of a melt particle, but describes the principal direction of the material flow. One can conclude from the flow lines that biaxial orientation may be assumed near the gate. At some distance from the gate, there is no tangential elongation in the case illustrated in the figure and the melt particles are oriented primarily by shear deformation in the direction of flow.

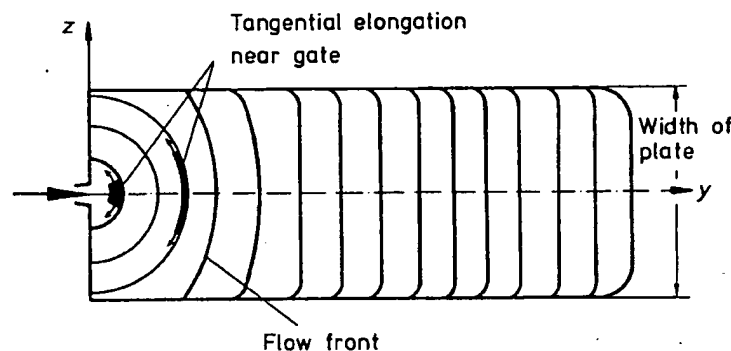


Figure 24 Form of the flow front at various moments during filling of a plate mold [11].

The complexity of orientation becomes even more obvious if a cross section is examined. The maximum shear velocity and orientation are just underneath a thin layer adhering to the cavity wall. With increasing growth of the solid layer, the orientation maximum moves toward the center.

The conditions in the flow-front region cause a biaxial elongation and orientation (Fig. 25). The melt flows transversely to the axial direction [15], and the relatively highly viscous plastic is biaxially stretched like a skin. This causes an orientation which is immediately frozen in

Figure 2

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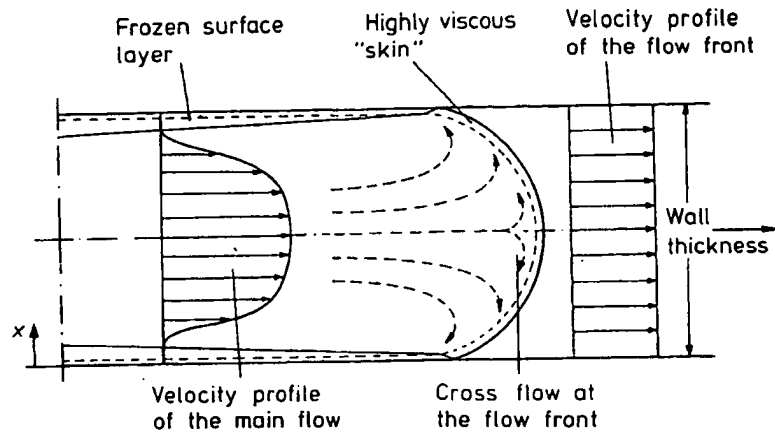


Figure 25 Velocity profile in a longitudinal cross section [13].

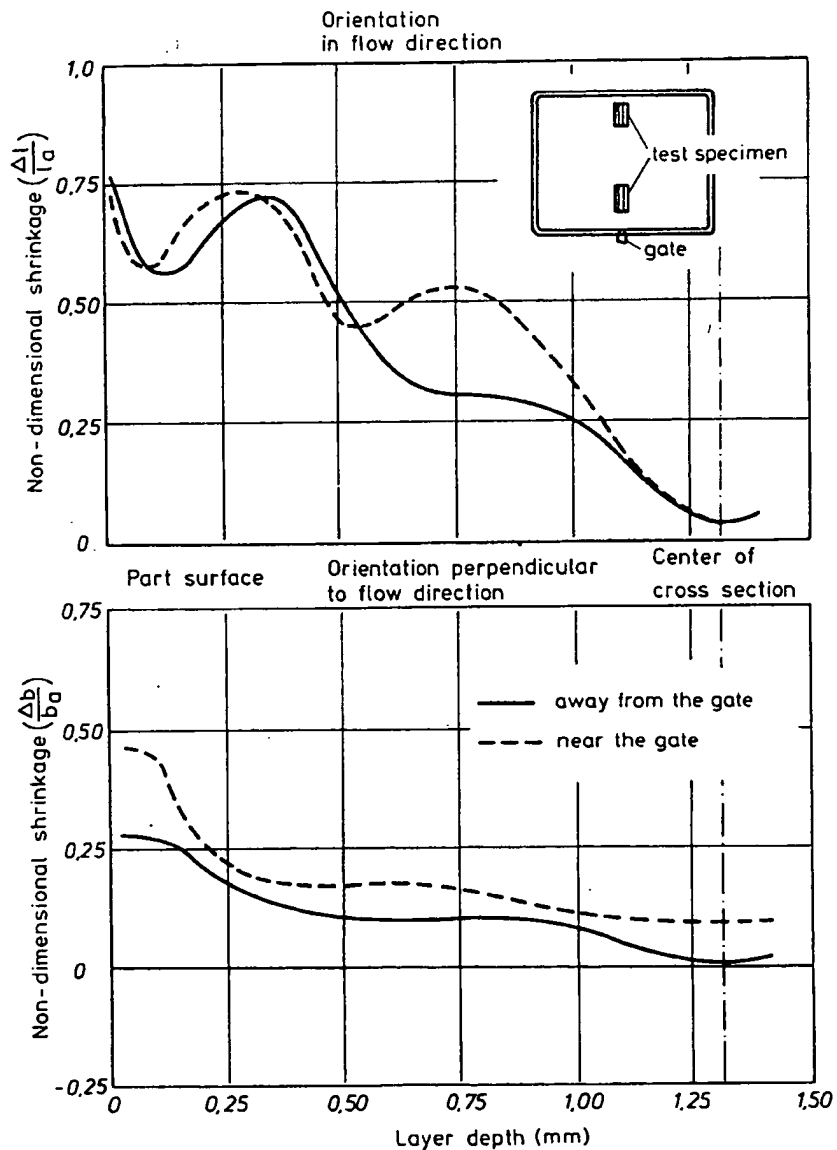
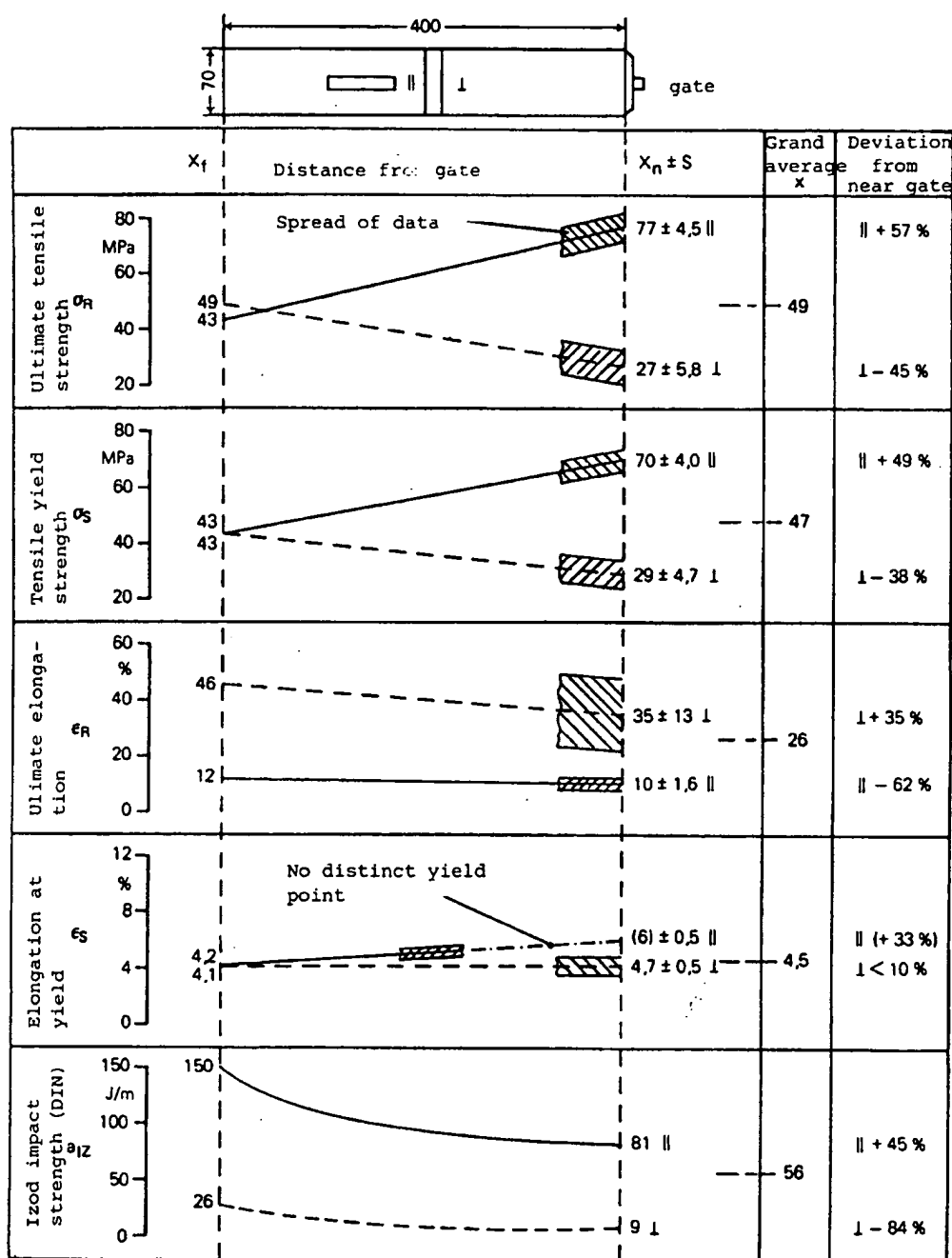


Figure 26 Shrinkage variations in a polystyrene molding. Shrinkage close to and away from the gate [15].

Injection molded cellulose acetate

Wall thickness: 2 mm
Melt temperature: 215°C
Mold temperature: 50°C
Velocity of flow front: 80 cm/s
Max. cavity pressure: $4,8 \times 10^7$ Pa



X_f - Result far from gate X_n - Result near gate S - Standard deviation

Figure 27 Mechanical properties of a molded part in relation to distance from gate and direction of flow [18].

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when the material comes in contact with the cavity wall and results in an additional transverse orientation in the part surface. An orientation of this kind can be demonstrated by heating slices of the part above the glass transition temperature and plotting the distribution of the observed shrinkage (Fig. 26).

In the vicinity of the gate, orientation can be found in the cross section almost as deep as the center, which is attributed to the tangential orientation just discussed [15]. Longitudinal orientation frequently has a second maximum further inside the part that results from melt flow during the holding pressure stage. Altogether, the degree of orientation is higher in the vicinity of the gate than away from it.

The molder has to understand the effect of orientation and should know that the orientation of molecular chains can often result in a marked anisotropy of the majority of part properties. This becomes especially noticeable in mechanical properties. The strength is always higher in the direction of orientation than perpendicular to it. Frequently such an effect is desired, but every so often it is not because of reduced strength in the transverse direction. Figure 27 presents an example of how mechanical properties can vary according to the distance from the gate and the flow direction. The effect on tensile and impact behavior is evident. Table 2 provides information about the relationship between processing parameters and degree of orientation and anisotropy.

Orientation does not produce autonomous (independent) residual stresses at temperatures of common use (refer to the following section).

The orientation of fillers occurs in the same way as molecular orientation. Especially fibrous fillers cause large-scale anisotropy of properties. The ranges of deviation from mean values are presented in Fig. 28.

2.4.2.2 Residual Stresses

Residual or internal stresses are mechanical stresses that are present in a part in the absence of external loading. They result from changes from the position of equilibrium of atoms and the distortion of valence angles in the molecular chains, as well as from changes in the distances between segments of the molecule (secondary bonds). Deformations which cause residual stresses are of an energy-elastic nature. The strains associated with them are smaller than the yield

Table 2 Effect of Processing Parameters on Orientation and Anisotropy

Processing parameter	Effect	Degree of orientation	Anisotropy
Increasing melt temperature	Increased relaxation time	↓	↓
Increasing mold temperature	Increased relaxation time	↓	↓
Increasing injection speed	Very thin surface layer Increased relaxation time in the core	↓ ↓	↓ ↓
Increasing holding pressure	Relaxation impeded, increased degree of cooling during injection of melt	↑ In part interior	↑
Geometry			
Increasing wall thickness	Smaller shear rate, long relaxation time	↓	↓
Extremely thin wall	Calls for high injection speed, orientation in surface layer predominant	↑ ↑	↑ ↑
Varying wall thickness	Same as above	↑ ↓	↑
Cross section of gate	Indirect effects, by way of injection speed, holding pressure, melt temperature	↑ ↓	↑ ↓

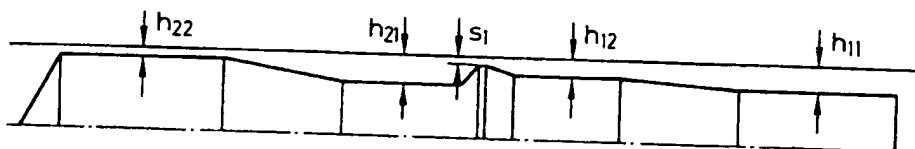
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section. This is achieved partly by dividing the screw appropriately into zones and partly by selecting suitable flight depth, pitch, and clearance of shearing sections. Additional metering devices can compensate for insufficient coordination by design although they promote operating errors and constitute a potential source of trouble. Varying the screw geometry is sometimes suggested as a way of adapting to the viscosity of a particular material [43]. Practical experience has shown, however, that a wide range of plastics with different melt viscosities can be processed satisfactorily with a uniform screw geometry and without additional metering devices. Such screws are depicted with Fig. 46. Their division into zones and a pitch of 0.7 times the screw diameter (D) in the first stage have proved satisfactory for diameters between 25 and 70 mm. If the diameter exceeds 70 mm, a pitch of 0.8 D provides better results. The second stage usually has a pitch equal to the diameter.

Table 9 Flight Depth and Clearance at Shear Element of Screw for Vented Barrel with L/D ratio of 20 : 1^a



Diameter (mm)	Flight depth h_{11}	Flight depth h_{12}	Flight depth ratio	Flight depth h_{21}	Flight depth h_{22}	Flight depth ratio	Shear gap width s_1
30	4.0	2.0	2 : 1	6.3	2.2	2.85 : 1	0.5
50	5.4	2.7	2 : 1	9.3	3.2	2.9 : 1	0.8
70	7.0	3.2	2.2 : 1	11.7	3.9	3 : 1	1.0
100	9.0	4.1	2.2 : 1	15.1	5.0	3 : 1	1.3
120	9.6	4.4	2.2 : 1	15.1	5.0	3 : 1	1.5
145	11.7	5.4	2.1 : 1	15.1	5.0	3 : 1	1.7

^a Model law: $h_x = h_0(D_x/D_0)^{0.7}$

$R_1 \sim 2-3$ mm, $R_2 \geq 10$ mm for up to 60 mm dia ≥ 15 for more than 60 mm dia

Table 9 shows flight depths for screws tested under practical conditions. Values for intermediate diameters can be calculated with sufficient accuracy using the formula [37, 38]:

$$h_x = h_0 \left(\frac{D_x}{D_0} \right)^{0.7} \quad (\text{you may use also exponent } 0.74)$$

where h_x = flight depth required, D_x = diameter required, h_0 = known flight depth, D_0 = known diameter.